EFFECT OF GRADE ON LOAD DURATION OF DOUGLAS-FIR LUMBER IN BENDING

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ABSTRACT

Select Structural, No. 2, and No. 3 Douglas-fir 2 by 4 specimens were tested in bending at several rates of loading and several levels of constant load to determine the effect of grade on load duration. The constant load results suggest that lower grades of lumber have shorter times to failure; however, differences in the load duration effect between lumber grades may not be statistically significant. These results also suggest that allowable bending properties of lumber may be nonconservative for any design load that really exists for the design duration. Recommended load duration design factors based on traditional methods of derivation are included along with discussion of stress level threshold and absolute stress effect. This report should be useful to engineers responsible for wood structural design and to grading agencies for evaluating the safety of recommended allowable lumber properties, from the standpoint of both real loads and their durations as well as code loads.

Keywords: Static strength, grade, rate of loading, duration of load, constant load, bending, lumber, time.

INTRODUCTION

The Forest Products Laboratory of the USDA Forest Service has an ongoing research program to evaluate the effects of duration of load in structural lumber. The several objectives of this research program include:

1. Developing a constant load duration relationship for lumber.
2. Evaluating effects of factors such as grade, treatment, temperature, and relative humidity on load duration.
3. Evaluating a cumulative damage model that theoretically relates damage to load history, thereby providing a relationship between the effects of rate of load and constant load.

This paper is concerned with the constant load duration relationship for lumber and the effect of lumber grade on that relationship. A later paper will evaluate the cumulative damage analysis of the research results.

Early research on load duration dealt mostly with effects in clear wood (Gerhards 1977). This research showed that lower applied stresses resulted in longer times to failure and that even a small difference in applied stress greatly changed the time to failure. Constant load test results were generally modeled with an exponential of the form

$$T = \exp(a - b\ SL) \tag{1}$$

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where T is time on constant load to failure, SL is applied stress relative to predicted static strength, and a and b are constants.

Rather than the exponential model, the load duration design curve for lumber [NFPA 1986, National Design Specification (NDS)] is the power model

$$T = \frac{SL - C^{B}}{A} \tag{2}$$

where T and SL have the same meaning as above and A, B, and C are constants. Equation (2) was developed with the concept that a single curve should relate constant load, rate of load, and impact load results, with the additional condition of a threshold stress level such that failure would never occur if SL was $\leq$C (Wood 1951).

Although the load duration design curve is based on data for clear wood, it is used to support various factors to adjust published allowable design stresses for lumber for different design load durations (e.g., wind, earthquake, snow). Published allowable design stresses for normal loading (implies a 10-year design load duration) are set about 40% below static strength values. The adjustment factors permit an increase in allowable stresses for design loads of shorter duration than 10 years but require a decrease for permanent loads (NDS).

In the early 1970s Madsen questioned the need for load duration adjustments of allowable design values in bending and shear (Madsen 1971, 1972a). Madsen inferred from pseudoramp tests at various rates of loading that weak lumber did not have a load duration effect, whereas strong lumber demonstrated the same kind of load duration effect as clear wood. Thus, because allowable properties are based on the weaker pieces in a lumber grade, Madsen thought that a load duration factor was not needed in the design process. Later, Madsen inferred that tension perpendicular to grain exerted a strong load duration effect regardless of strength level (Madsen 1972b). This conclusion was based on pseudoramp tests of glulam beam sections in tension perpendicular to grain. Subsequent tests of small and large wood sections under constant tension perpendicular loads confirmed Madsen's results (Mau 1976).

Madsen's conclusion that there is no load duration effect in bending at the design level inspired more in-depth research into the effect of load duration on strength of lumber. This report presents an evaluation of recent results from bending tests of three structural grades of Douglas-fir 2 by 4s under constant load.

PROCEDURE

Lumber

A total of 3,600 Douglas-fir 2 by 4 specimens were obtained from a lumber mill in Oregon. Half of the specimens were 8 feet long and the other half were 10 feet long. The specimens were selected on the basis of certain knot size and position criteria from lumber that was produced S-GN (i.e., surfaced in the green condition) over a period of 2 weeks.

The lumber was kiln-dried using a mild kiln schedule. All specimens were further conditioned for many months at 73 F and 50% relative humidity. The 10-foot-long specimens were then trimmed to 8 feet. Modulus of elasticity was determined for each specimen under edgewise bending with a support span of 7

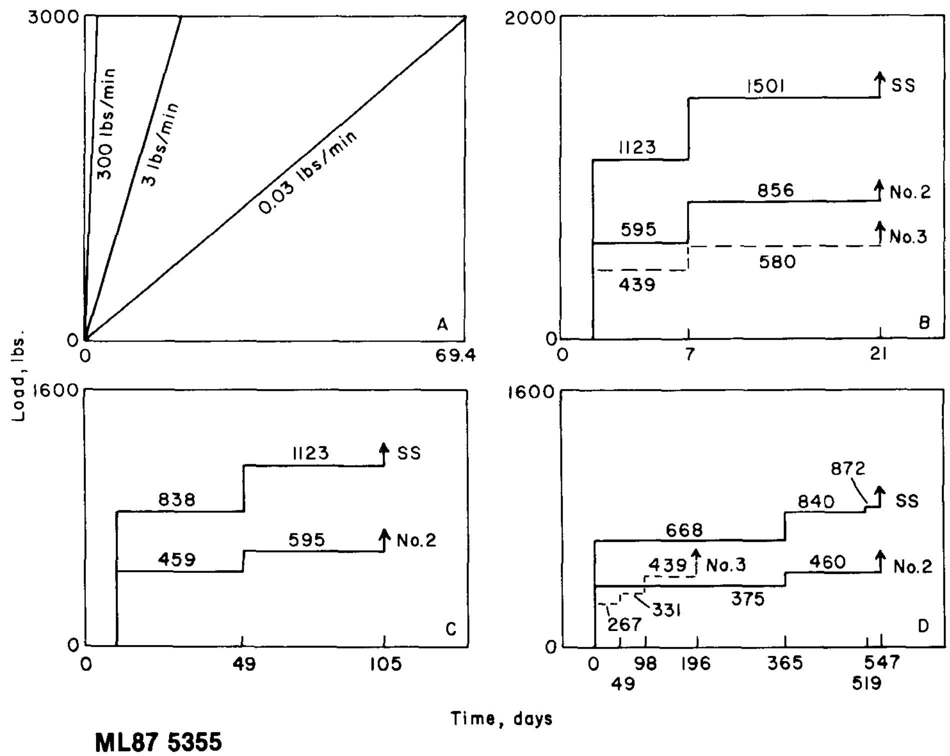


FIG. 1. Load history test regimes: A—ramp load in pounds per minute, B—high step-constant load in pounds, C—medium step-constant load in pounds, D—low step-constant load in pounds. Change in constant load levels at 300 pounds per minute. One pound = 5.13 psi bending stress. (ML87 5355)

feet; two load points spaced 2 feet apart were centrally located on the support span. In addition, each specimen was assigned a bending strength ratio (ASTM 1981) based on the strength-controlling knot that had been used in specimen selection. The strength-controlling knot was located within the central 30-inch length. Warp was also measured.

Nondestructive evaluation of the specimens revealed that the lumber was distributed among four stress grades (Select Structural (SS), No. 1, No. 2, and No. 3) on the basis of bending strength ratio, and the lumber was sorted by these grades. Specimens were culled for excessive warp (bow >0.3 in. and crook >0.5 in.) to avoid problems in performing bending tests. To control strength variation, SS specimens were also culled if the bending strength ratio was greater than 85%.

Within each grade the usable specimens were ranked according to modulus of elasticity (ESORT), and within modulus of elasticity, according to bending strength ratio. The ranked specimens were divided into sets (SS, 59 sets; No. 1, 27; No. 2, 25; and No. 3, 24) so that the specimens of a given set had nearly identical moduli of elasticity and bending strength ratios. Specimens with extremely low and extremely high moduli were excluded to control strength variation. One specimen was randomly selected from each set and assigned to a group. Thus, 59 groups of SS, 27 groups of No. 1, 25 groups of No. 2, and 24 groups of No. 3 specimens were segregated. Each group contained 25 specimens such that all

TABLE 1. *Number of specimen groups allocated for different tests.*[1]

Load history	Grade		
	Select Structural	No. 2	No. 3
Fast ramp	4	4	4
Medium ramp	2	2	—
Slow ramp	4	4	—
High step-constant	2	2	2
Medium step-constant	2	2	—
Low step-constant	2	2	2
10-year constant	2	2	—

[1] Each group contained 25 specimens.

groups of a given grade had similar distributions of moduli and strength ratios. Specimens from the SS, No. 2, and No. 3 groups were used for this study.

Loading tests

Specimens were tested under the following load history types: three rates of ramp loading (fast, medium, or slow) and three levels of step-constant loading (high, medium, or low) (Fig. 1). These load histories were conducted at constant 73 F, with 50% relative humidity. In addition, tests of 10-year constant load duration are presently being conducted in an unheated building.

Table 1 shows the number of specimen groups allocated for each test. A total of 400 SS, 400 No. 2, and 200 No. 3 specimens were tested under constant environmental conditions, excluding the specimens for the 10-year constant load tests.

The actual configuration for each bending test was the same as that used to determine edgewise modulus of elasticity. Except for the specimens in the 10-year constant load tests, all specimens were tested in three 50-frame test setups (Fig. 2). Each frame was equipped with a near friction-free air cylinder for applying load, a potentiometer for monitoring deflection, and a clock for timing failure. Thus, the air cylinders, capable of applying ramp as well as constant load, simulated dead load. Each of the 50-frame setups included a dummy frame, which contained a load cell in series with an air cylinder of the same type. Airline pressure on the cylinder was reflected as specimen load on the load cell. The 10-year tests are being conducted with dead load suspended from each specimen. All specimens, whether ramp or constant load, were tested with the grade-controlling knot on the beam tension side. All uploading to the various step-constant load levels was at the rapid loading rate (300 lb/min). In addition to load and time at failure, modulus of elasticity (ETEST) was determined for each specimen from load-deflection data recorded during a load history run. Load-deflection data were not obtained for one No. 2 and one No. 3 run.

RESULTS AND DISCUSSION

Results from the tests using three rates of ramp load on SS and No. 2 specimens were presented in a previous report (Gerhards and Link 1986), which pertained to the effect of constant load relative to static bending strength. Therefore, the data on constant load failures, including the early 10-year constant load and the rapid ramp failures, are pertinent to the results reported here. Results on physical

FIG. 2. Bending test-frame setup. (M83 0172-2)

properties of the test specimens are summarized in Table 2. ESORT values averaged about 5% higher than ETEST values, perhaps a result of using a low nondestructive load to measure ESORT.

Traditionally, constant load durations have been presented in relation to applied stress relative to static strength. The "normalized" results, based on one limited set of conditions (clear wood, bending), have been applied to lumber independent of species, grade, size, or loading mode (tension, bending, compression, shear). Obviously, constant load duration and static strength for a given specimen cannot be tested simultaneously. The static strength of each specimen that fails under constant load must therefore be estimated.

Static strength of ramp load failure specimens

In this study, the rapid ramp load test results were originally used to estimate static strengths of specimens tested under step-constant load. The constant loads were estimated at the following percentiles of the rapid ramp "static strength" distributions: Fig. 1B: 40th–70th percentile for SS, No. 2, No. 3; Fig. 1C: 15th–40th percentile for SS, No. 2; Fig. 1D: 5th–15th percentile for SS, No. 2, 5th–15th–40th percentile for No. 3; and 10-year: 5th ÷ 1.62 SS, No. 2. Except for the 10-year constant load specimens, some specimens failed at loads below the first

TABLE 2. *Physical properties of test specimens.*[1]

Load history	Number of specimens	Moisture content (%)	Specific gravity[2]	Modulus of elasticity ESORT	Modulus of elasticity ETEST
				(10⁶ psi)	
		Select Structural			
Fast ramp	100	9.5 (0.39)	0.453 (0.041)	2.00 (0.31)	1.94 (0.30)
High constant	50	9.7 (0.45)	0.456 (0.035)	1.99 (0.31)	1.89 (0.30)
Medium constant	50	10.0 (0.35)	0.459 (0.044)	2.00 (0.30)	1.89 (0.28)
Low constant	50	10.0 (0.43)	0.470 (0.049)	2.00 (0.33)	1.89 (0.31)
		No. 2			
Fast ramp	100	9.5 (0.47)	0.451 (0.034)	1.50 (0.27)	1.44 (0.26)
High constant	50	9.7 (0.42)	0.448 (0.036)	1.50 (0.27)	1.41 (0.25)
Medium constant	50	10.0 (0.40)	0.456 (0.042)	1.49 (0.27)	— —
Low constant	50	9.9 (0.49)	0.452 (0.034)	1.49 (0.26)	1.47 (0.22)
		No. 3			
Fast ramp	100	9.6 (0.46)	0.449 (0.037)	1.41 (0.28)	1.36 (0.25)
High constant	50	9.8 (0.39)	0.452 (0.028)	1.42 (0.27)	1.36 (0.25)
Low constant	50	9.8 (0.41)	0.455 (0.034)	1.41 (0.26)	— —

[1] Average values and standard deviations (in parentheses).
[2] Based on test volume and oven-dry weight.

load level of each step-constant load history, as expected. For example, about 40% of the specimens were expected to fail before the 40th percentile static strength load level was attained.

All "static strengths" of specimens that failed during ramp uploading to the first constant load level of a given load history were used to improve the estimate of static strength of specimens that failed under constant load. All ramp load failures of each load history series were assigned a number according to ranked failure loads: i = 1 for the lowest strength, i = 2 for the second lowest, on up to i = n for the highest strength of ramp upload failures. A probability, *P*, was calculated for each specimen according to the formula

$$P = \frac{i - 0.375}{N + 0.25} \tag{3}$$

where N is the total number of specimens tested in the load history series. A normal score, *R*, was obtained from a cumulative normal distribution table of *P*s for each ramp upload failure. *R* is also known as the standard normal variable and has example values of 0 for the median and −1.645 for the 5th percentile. A plot of the logarithm of static strength (LnML) versus *R* should thus be a straight line if static strength is lognormally distributed.

The various series of LnML-*R* data for a grade were combined to form the cumulative distribution of static strength shown in Figs. 3, 4, and 5. The lognormal seems a reasonable assumption for the static strength distributions of each of the three grades of lumber. The scatter of data in the lower half of the cumulative distributions ($R < 0$) represents the input of ramp load failures from the step-constant load series combined with the input of the rapid ramp load test series. The lines plotted through the data in Figs. 3, 4, and 5 represent the regression of LnML on *R*. Least squares regressions are:

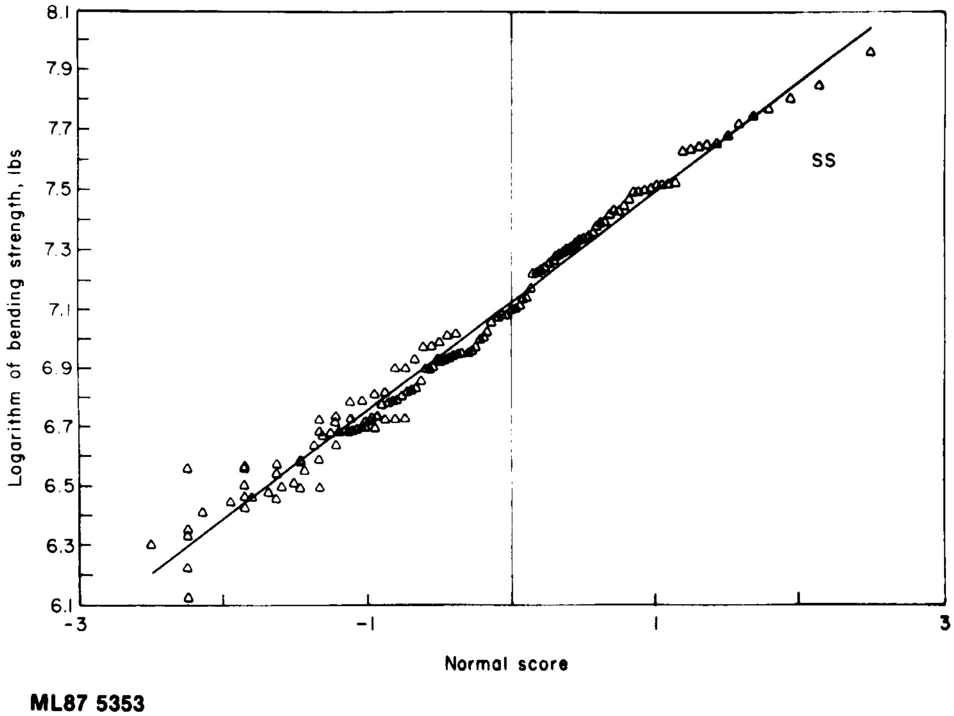


FIG. 3. Cumulative distribution of the natural logarithm of static bending strength (LnML) in pounds for Select Structural specimens. One pound = 5.13 psi bending stress. (ML87-5353)

$$\text{SS} \quad \text{LnML} = 7.123296 + 0.368201R \tag{4}$$

$$\text{No. 2} \quad \text{LnML} = 6.443158 + 0.365746R \tag{5}$$

$$\text{No. 3} \quad \text{LnML} = 6.174397 + 0.369454R. \tag{6}$$

Median static strengths calculated from Eqs. (4), (5), and (6) were: 1,240.5 pounds for SS, 628.4 pounds for No. 2, and 480.3 pounds for No. 3 specimens. All three grades of lumber had about the same coefficient of variation (COV) in static strength because the coefficients of R in the three equations are close approximations of COV. Median times to failure calculated from Eqs. (4), (5), and (6) and rapid rate were 4.1 minutes for SS, 2.1 minutes for No. 2, and 1.6 minutes for No. 3 specimens.

Predicted static strength of constant load failure specimens

The least squares regressions of LnML on R were used to predict static bending strength of all specimens that failed under constant load, based on the assumption that specimens that fail under constant load would have the same rank in time as they would have in static strength (equal rank assumption). The constant load failures within a load history series were assigned a rank number according to ranked times to failure beginning with $i = n + 1$ to $i = n_c$, where n is the number of the highest strength specimen failing on ramp uploading as defined previously and n_c is the last specimen of the series to fail under constant load before surviving

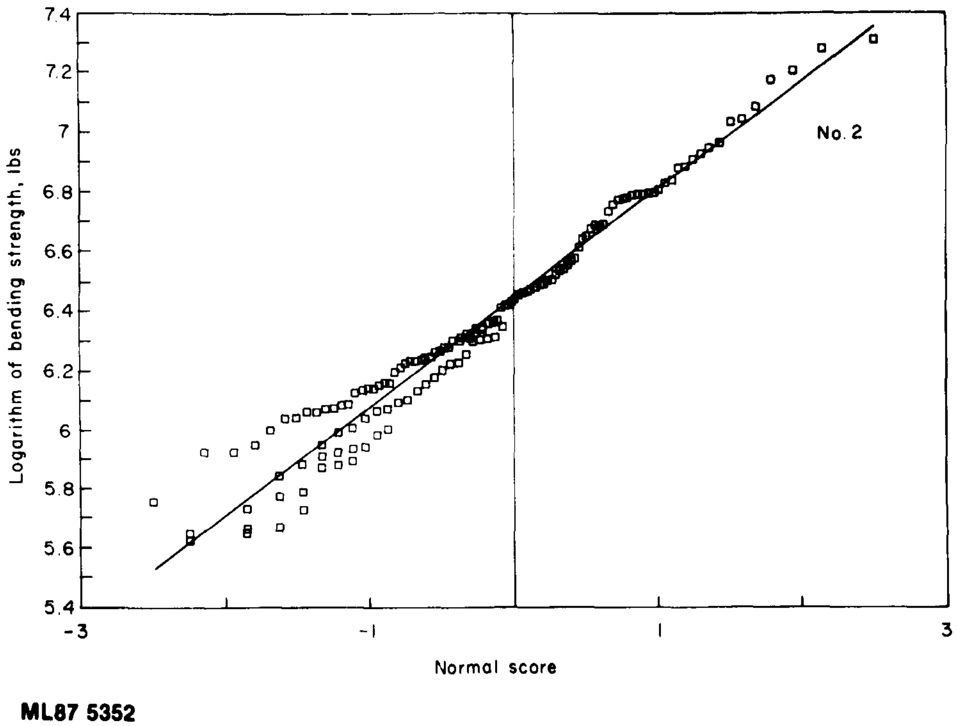


FIG. 4. Cumulative distribution of the natural logarithm of static bending strength (LnML) in pounds for No. 2 specimens. One pound = 5.13 psi bending stress. (ML87 5352)

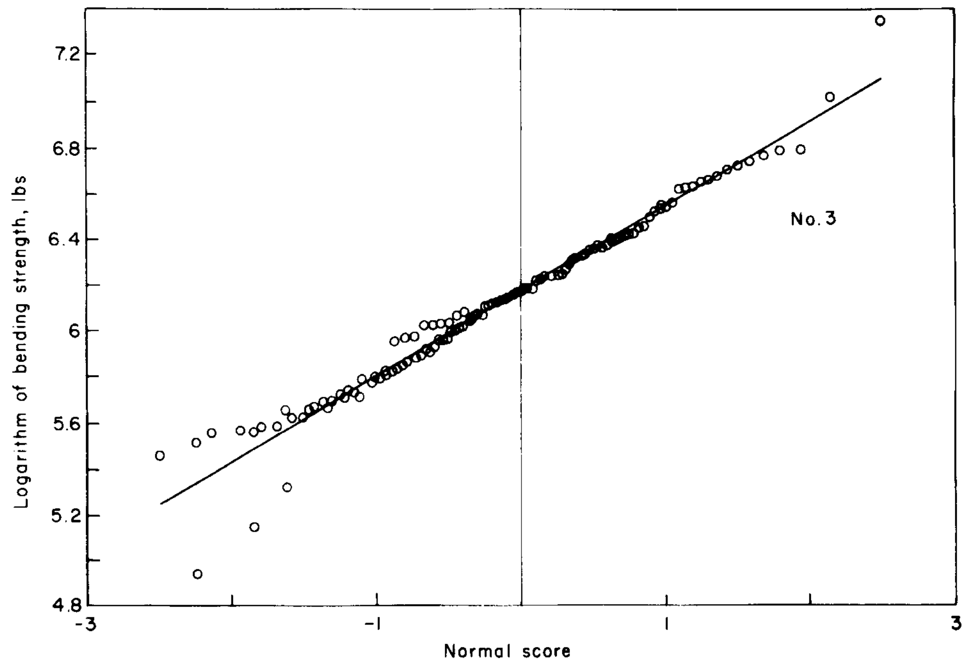
specimens were tested to failure in rapid ramp loading. As for the static strength specimens, P was calculated from Eq. (3) and the corresponding value of R was assigned to each specimen that failed on constant loading. The static strength of constant load failures was then predicted by Eqs. (4), (5), or (6) according to grade and assigned value of R.

Stress level

Traditionally, constant load durations have been presented as a function of stress level (SL), which is defined as applied stress divided by predicted static strength. This normalization of applied stress is desirable; for example, it allows direct comparison of load durations across grades, species, and modes of loading. Therefore, the stress level for a specimen that failed under constant load was calculated as the constant load that caused failure divided by the predicted static strength of the specimen.

Time to failure as a function of stress level

Figures 6, 7, and 8 show stress level plotted against the natural logarithm of time on constant load (LnTC) by grade. A regression line (——) is shown for each grade, and an alternate regression line (-----) is shown with SL as dependent variable. The data include all specimens that failed under constant load. Arrows indicate incompletely tested specimens, i.e., those that survived the load durations shown in Fig. 1. The time used for a given data point represents only the time



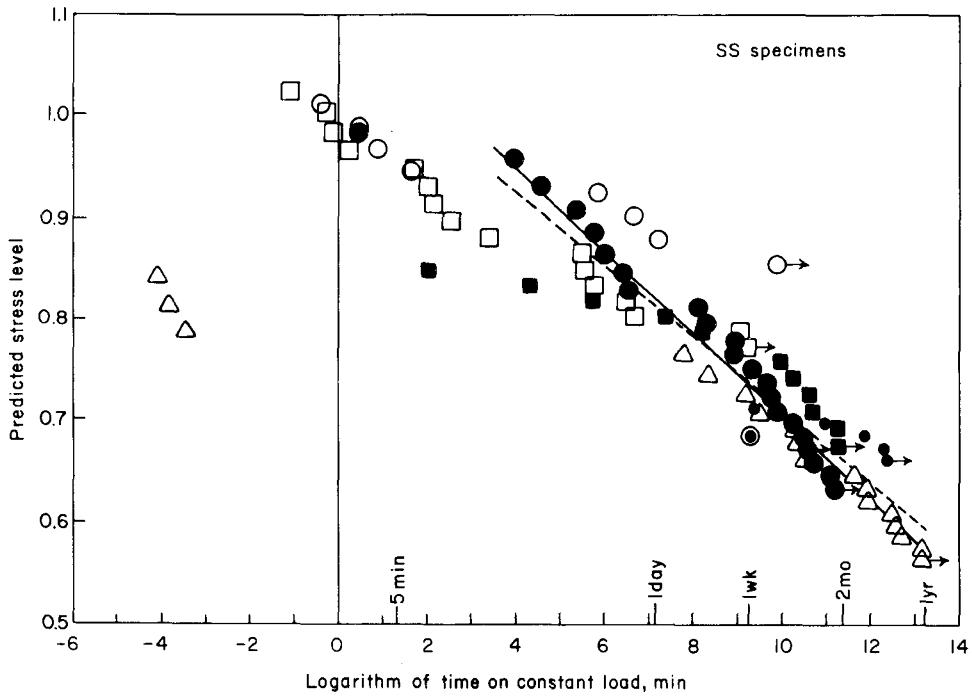
ML87 5351

FIG. 5. Cumulative distribution of the natural logarithm of static bending strength (LnML) in pounds for No. 3 specimens. One pound = 5.13 psi bending stress. (ML87 5351)

when the specimen failed. Thus, ramp uploading time or time spent at a lower step of a particular step-constant load history was subtracted from the total testing time.

Some of the results were different from those predicted. Some specimens failed earlier than expected; others had higher strength than predicted. The data points are scattered in Figs. 6, 7, and 8, even though the method used to predict stress level is thought to have the least possible bias. For example, in Fig. 6 the very early SS failures (outlying data points) had predicted SLs from about 0.78 to 0.84; however, such early failures should not occur at real SLs of those magnitudes. Rather, an SL of about 0.99 would be appropriate. The most likely explanation for the early failure of these SS specimens is that their actual strengths were lower than those predicted. On the other hand, the actual strength of one incompletely tested SS specimen in the high step-constant load series was higher than predicted (predicted SL = 0.85 and LnTC = 9.9). Residual strength of that survivor was 6.4% greater than the predicted static strength. Had that specimen failed at the plotted time, its real SL $\leq$ 0.80 would have been unknown. Two other SS specimens had predicted SL $>$ 1.0; one of these had a predicted SL of 1.02. (Two No. 3 specimens also had predicted SL $>$ 1.0.) By definition, SL must be less than 1.0 when ramp uploading is at the same rate that is used for static strength. However, although predicted SLs are somewhat uncertain, most predicted values are probably within $\pm$3% of the true SLs.

Another result was the lack of any evidence of an SL threshold, at least in the



ML87 5350

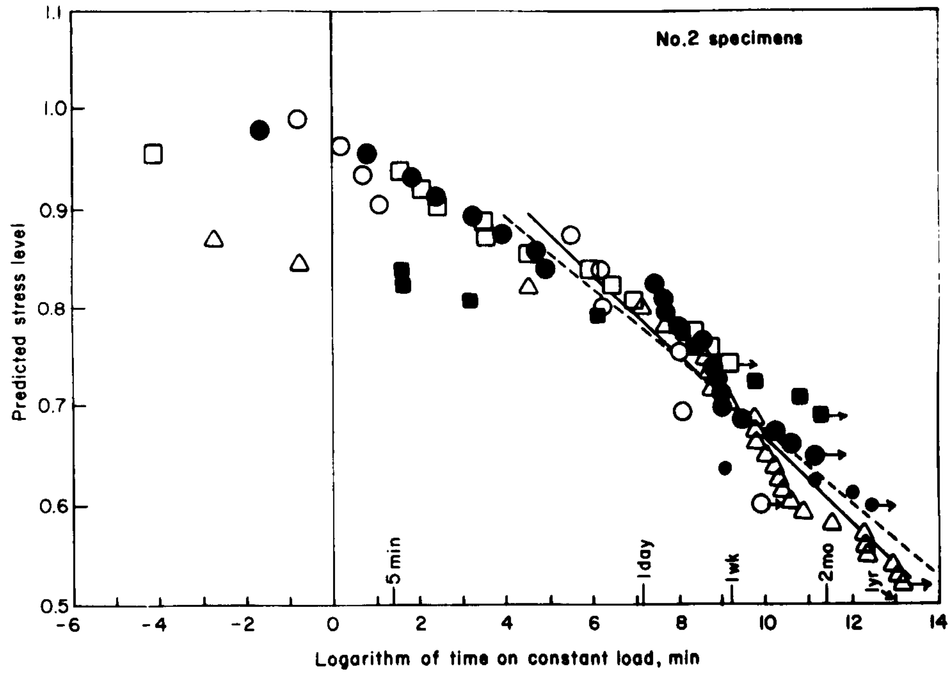
FIG. 6. Relation between time to failure and stress level in Select Structural (SS) specimens. Arrows indicate incomplete tests. Solid line indicates regression; broken line indicates alternate regression with SL as dependent variable. Data points indicate constant load in pounds: △, 668 lb; ● ●, 840, 838; ■ □, 1,123; ○, 1,501. (ML87 5350)

lower SL range of 0.51 to 0.55. The existence of a threshold, that is, that a specimen would never fail if SL ≤ the threshold (Foschi and Barrett 1982), is difficult to prove; it would be necessary to test specimens for 10 to 100 years, perhaps even a thousand years, at SLs lower than 0.5.

Finally, there is no evidence that the SL − LnTC relation is inversely affected by applied stress as suggested by a load duration fracture mechanics model (Johns and Madsen 1982). Given that SL is some constant value, the fracture mechanics model predicts shorter durations for specimens subjected to higher applied stress than for those subjected to lower applied stress. If anything, the data for No. 3 specimens (Fig. 8) suggest the opposite trend. Data for the SS and No. 2 specimens do not show a consistent relationship between stress level and time.

Regressions of LnTC on SL

The solid regression lines shown in Figs. 6, 7, and 8 were fit with LnTC as the dependent variable and SL as the independent variable. SL was chosen as the independent variable because engineers are interested in determining the useful life of lumber at some specified load or SL. The alternate regressions with SL as dependent variable, shown as broken lines in Figs. 6, 7, and 8 for the reader's convenience, are not considered further. Incomplete test data were excluded in



ML87 5349

FIG. 7. Relation between time to failure and stress level in No. 2 specimens. Arrows indicate incomplete tests. Solid line indicates regression; broken line indicates alternate regression with SL as dependent variable. Data points indicate constant load in pounds: △, 375 lb; ● ●, 460, 459; ■ □, 595; ○, 856. (ML87 5349)

the least squares analyses. Also excluded were data with LnTC < 3 (implies 20 min) because of the probable shortening of constant load time due to uploading effects. Equations for the lines with standard errors (S_e) of intercept and slope and standard deviation about regression (S) are

$$\text{SS LnTC} = 27.4382 - 24.7090\text{SL} \tag{7}$$

$$S_e \text{ intercept} = 0.8968,\ S_e \text{ slope} = 1.1814,\ S = 0.8516$$

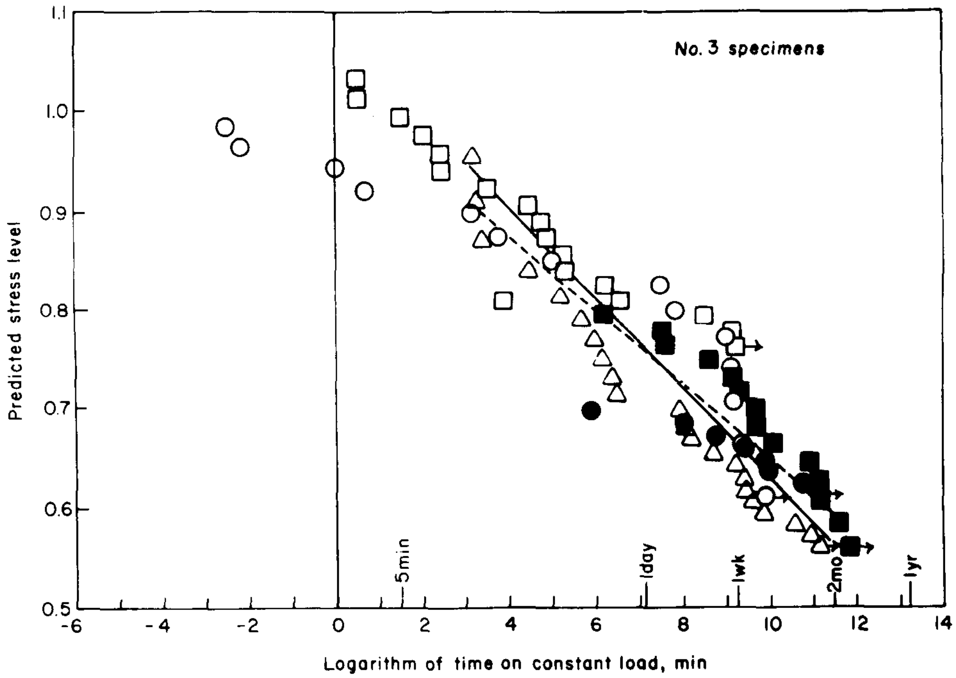
$$\text{No. 2 LnTC} = 25.9539 - 24.0309\text{SL} \tag{8}$$

$$S_e \text{ intercept} = 0.8646,\ S_e \text{ slope} = 1.1744,\ S = 0.8948$$

$$\text{No. 3 LnTC} = 23.6222 - 21.7119\text{SL} \tag{9}$$

$$S_e \text{ intercept} = 1.1393,\ S_e \text{ slope} = 1.3253,\ S = 1.0364.$$

Based on the 95% confidence limits on intercepts and slopes (Table 3) calculated from the data, SS and No. 2 data do not have significantly different regressions; however, the SS data have a significantly different regression from No. 3 data, and the intercepts for No. 2 and No. 3 data are significantly different. Two factors may reduce apparent significant differences. One factor is the effect of unknown variation in predicted SL on larger confidence limits. The other factor pertains



ML87 5348

FIG. 8. Relation between time to failure and stress level in No. 3 specimens. Arrows indicate incomplete tests. Solid line indicates regression; broken line indicates alternate regression with SL as dependent variable. Data points indicate constant load in pounds: △, 267 lb; ●, 331; ■□, 439; ○, 580. (ML87 5348)

to rate of loading for static strength. All three grades were loaded at the same rate. Had No. 2 and No. 3 specimens been tested at a rate of loading calculated to give the same median time to failure for SS, then static strengths would be about 3% lower for No. 2 specimens and about 4% lower for No. 3 specimens than actually measured, assuming the rate of loading effect parallels the constant loading effect. Thus, coefficients would be 3% higher for Eq. (8) and 4% higher for Eq. (9). Despite these adjustments, the trend in the LnTC − SL regressions indicates that lower grades have shorter times to failure.

The transpositions of Eqs. (7), (8), and (9) expressed in both natural and base 10 logarithms are

$$\text{SS} \quad \text{SL} = 1.110 - 0.0405 \text{ LnTC} \qquad (10)$$

$$\text{SL} = 1.110 - 0.0932 \text{ Log TC}$$

$$\text{No. 2} \quad \text{SL} = 1.080 - 0.0416 \text{ LnTC} \qquad (11)$$

$$\text{SL} = 1.080 - 0.0958 \text{ Log TC}$$

$$\text{No. 3} \quad \text{SL} = 1.088 - 0.0461 \text{ LnTC} \qquad (12)$$

$$\text{SL} = 1.088 - 0.1061 \text{ Log TC}.$$

For comparison, SL = 0.981 − 0.058 Log TC (LnTC = 38.945 − 39.700 SL) has

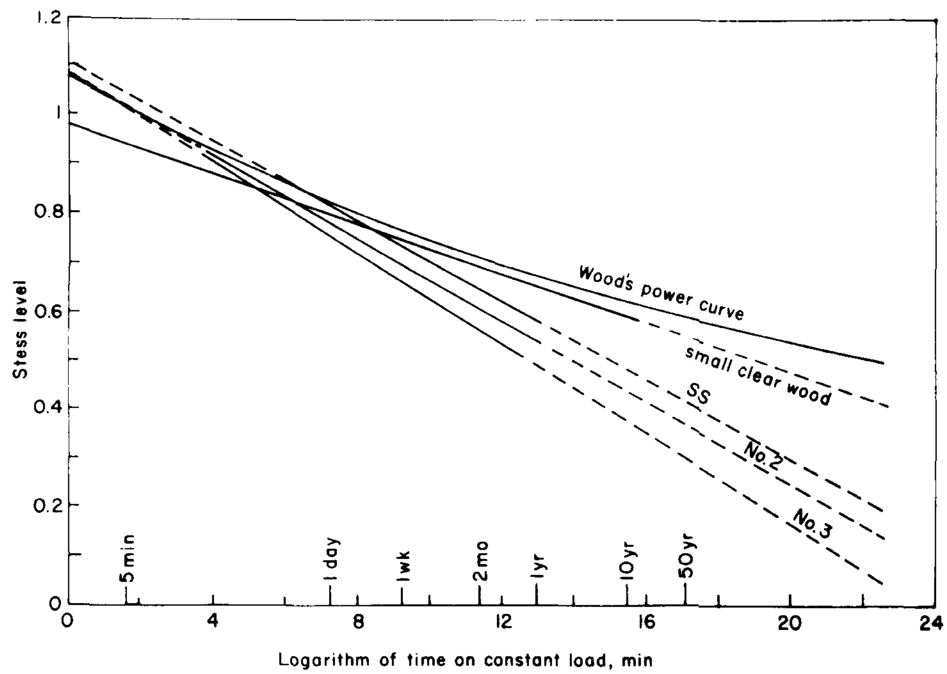
TABLE 3. *95% confidence limits on regression intercepts and slopes.*

Specimen grade	Number of specimens	Intercept	Slope
Select Structural	59	25.645; 29.232	−27.072; −22.346
No. 2	64	24.225; 27.683	−26.380; −21.682
No. 3	60	21.344; 25.901	−24.363; −19.061

been reported for clear wood under constant bending load (Gerhards 1977). The power curve proposed by Wood (1951) and used to set load-duration design factors for wood structures (NDS) is $SL = 0.183 + 0.8966/(TC^{0.04635})$. All of the above equations, expressed with TC in minutes, are compared in Fig. 9. The clear wood LnTC − SL intercept and slope lie outside the 95% confidence limits given in Table 3, suggesting a significantly different relation for clear wood than for lumber.

Proposed load duration design factors

Current load duration design factors (NDS) are 0.90 for permanent loads, 1.00 for 10-year loads, 1.15 for 2-month loads, 1.25 for 7-day loads, and 1.33 for 1-day loads regardless of loading mode, species, grade, or size of lumber. These factors are applied to the allowable lumber properties that are meant to safely support a 10-year design load for 10 years. For bending members, the allowable property is derived by dividing the fifth percentile static strength by 1.615 for 10-year load



ML87 5347

FIG. 9. Comparison of load duration models. Dashed segments represent extrapolation beyond the fitted data. (ML87 5347)

TABLE 4. *Predicted stress levels with estimated 95% confidence limits.*[1]

Constant load time	Predicted SLs				
	Select Structural	No. 2	No. 3	Clear wood	Wood's power curve
1 day	0.816 (0.80; 0.83)	0.777 (0.76; 0.79)	0.753 (0.74; 0.76)	0.798	0.823
1 week	0.737 (0.73; 0.75)	0.696 (0.69; 0.71)	0.663 (0.64; 0.68)	0.749	0.768
2 months	0.650 (0.64; 0.66)	0.607 (0.59; 0.62)	0.564 (0.54; 0.59)	0.695	0.712
10 years	0.484 (0.46; 0.51)	0.436 (0.40; 0.46)	0.375 (0.32; 0.42)	0.591	0.621
50 years	0.419 (0.38; 0.45)	0.369 (0.32; 0.40)	0.301 (0.24; 0.35)	0.551	0.589

[1] Upper and lower confidence limits are in parentheses.

duration and by 1.3 for a factor of safety. Except for the permanent load factor, the NDS load duration design factors are very close to factors derived from Wood's power curve. How do the NDS factors compare with factors similarly derived from the load duration equations of this study?

The development of load-duration design factors for the three grades of lumber in this study must take into account predicted SLs for the various load durations. Table 4 presents SLs along with 95% confidence limits determined from graphs of 95% confidence limits on time as a function of SL. Predicted SLs are included for Wood's power curve and for clear wood. A note of caution: the confidence limits on SLs are based on the data presented in Figs. 6, 7, and 8, with the assumption that times on constant load are lognormally distributed, and with the further assumption that the SLs in these figures are real rather than predicted. Thus, real 95% confidence limits on SLs are larger than those presented in Table 4 by an unknown amount. Also, note that the maximum time used is 50 years, whereas the "permanent" load duration factor of NDS represents about 300 years for Wood's power curve. In general the predicted SLs decrease with wood quality, and Wood's power curve predicts the highest SLs. The confidence limits suggest significant differences between grades.

Proposed load duration design factors for bending are presented in Table 5 for the three grades of lumber in this study. These factors were derived from the predicted SLs of Table 4, normalized at 10 years for comparison with current practice. Table 5 also includes values based on Wood's power curve, which generally agree with NDS values. Compared to NDS factors, the proposed factors are obviously higher for load durations shorter than 10 years but lower for longer durations. It is also apparent that the discrepancy between NDS factors and the proposed factors increases as grade quality decreases. Even though the proposed factors for short duration loads are higher than the NDS factors, practical application of the proposed factors requires greater reduction of strength values compared to the NDS basis reduction. For example, reductions in static strength are 38% for NDS, 52% for SS, 54% for No. 2, and 62% for No. 3. Consequently, actual design values will be lower when based on the proposed factors than when based on NDS factors, regardless of the design load duration considered. Note

TABLE 5. *Proposed load duration design factors for lumber in bending.*

Constant load time	Wood's power curve design factors	Proposed design factors		
		Select Structural	No. 2	No. 3
1 day	1.33	1.69	1.78	2.01
1 week	1.24	1.52	1.60	1.77
2 months	1.15	1.34	1.39	1.50
10 years	1.00	1.00	1.00	1.00
50 years	0.95	0.87	0.85	0.80

that the percent reductions in static strength do not include the additional safety factor reduction that is included in current allowable properties for lumber.

Design loads versus real loads

Structural design loads are specified in building codes. For example, the design snow load commonly has a cumulative duration of 2 months over the design life of a structure. If the design snow load is actually subjected to the 2-month duration, then an SS bending member will fail when its load is 65% of its static strength, a No. 2 member at 61%, and a No. 3 member at 56% (based on data in Table 4). This design snow load illustrates an important fact: whenever a structural member is loaded to its design equivalent SL for the full duration consistent with that SL, failure must be expected.

Real snow load durations measured over a 25-year period suggest that the design snow load rarely occurs. Thus, the effective design factors for snow load may be higher than the 2-month factors of Table 5. Effective factors can be derived by a complicated load-resistance factor design analysis. Such analysis (which is beyond the scope of this paper) has been considered for snow loads (Hendrickson et al. 1987) and light-frame floor loads (Murphy et al., 1987). In deriving allowable properties for lumber, grading associations need to use complicated load-resistance factor design to assess the impact of real loads and their durations on structural safety of wood products.

Preliminary results from 10-year tests

As mentioned earlier, 10-year constant load tests are being conducted in an uncontrolled environment on SS and No. 2 specimens matched to the static strength and step-constant load specimens used to derive Eqs. (7) through (12). The applied loads are 412.7 pounds for SS and 232 pounds for No. 2. These values, based on the static strengths of the rapid ramp series only, are thought to represent the respective fifth percentile static strengths divided by 1.62, with the expectation that 5% of the specimens will fail in 10 years. With the improved static strength predictors [Eqs. (4) and (5)], the loads multiplied by 1.62 represent the 5th percentile ($R = -1.68$) of SS static strengths but the 8th percentile ($R = -1.41$) of No. 2 static strengths. Without consideration of the 1.62 factors, the loads represent less than the 1st percentiles for both grades.

While none of the specimens failed during application of the dead loads, one SS specimen and six No. 2 specimens failed during the first 18 months; these specimens represent 2% and 12% of the SS and No. 2 specimens, respectively. While this failure rate appears excessive on the basis of the NDS 10-year load duration factor, particularly for No. 2 specimens, it is not inconsistent with results presented in Figs. 3, 4, and 5. Also, the fact that a specimen that would rank as low as the 2nd percentile (1 out of 50) in static strength actually failed under a constant load less than the 2nd percentile contradicts the Madsen hypothesis that low-strength pieces of a grade do not exhibit a load duration effect.

CONCLUSIONS

The results of this study give rise to several important conclusions:

(1) There is a constant load effect on lumber in bending, regardless of the static strength level.

(2) Lower grades of lumber loaded at the same fraction of static strength tend to have shorter load durations; however, differences between lumber grades evaluated in this study may not be statistically significant.

(3) Allowable bending properties for lumber appear to be nonconservative for any design load that really exists for the design duration. However, grading associations responsible for recommending allowable properties for lumber need to consider both real loads and their durations as well as code loads designed for product safety.

(4) There is no evidence of a stress level threshold below which there is no load duration effect. Absolute stress does not affect load duration if the effect of stress relative to static strength is taken into account.

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